[UCI]I804:24011-200000265708

2016 8월

석사학위 논문

불균일 분포 무선 센서 네트워크에서 노드 밀도 기반 트리 생성을 이용한 에너지 효율적 클러스터링 프로토콜

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An Energy-Efficient Clustering Protocol Using Density-Aware Tree Construction for Irregularly Deployed Wireless Sensor Networks

2016년 8월 25일

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지도교수 모 상 만

이 논문을 공학 석사학위 신청 논문으로 제출함

2016년 4월

조선대학교 대학원
컴퓨터공학과
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ABSTRACT

불균일 분포 무선 센서 네트워크에서 노드 밀도 기반 트리 생성을 이용한 에너지 효율적 클러스터링 프로토콜

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무선 센서 네트워크에서는 배터리로 작동하는 센서 노드의 에너지 소비를 줄이는 것이 네트워크 수명을 늘리는데 있어 매우 중요하다. 본 연구에서는 불규칙적으로 분포되는 무선 센서 네트워크의 에너지 소비를 감소시키기 위해 DAMC 프로토콜을 제안한다. 모든 노드는 주변의 노드 밀도를 바탕으로 스스로 클러스터 헤드가 될 확률을 결정한다. 따라서 클러스터 헤드는 네트워크 전체에 균등하게 분배되고 모든 클러스터는 거의 동일한 센싱 면적을 갖게 된다. 또한 밀도가 높은 지역의 일정 노드는 수면 모드로 전환된다. 그리고 각 클러스터 내에저 에너지 다중홉 전송을 위해 다단계 트리를 구성한다. DAMC에서는 불필요하게 소모적인 센싱과 전송이 현저하게 감소하고 클러스터 내에서 단일홉 전송보다는 다중홉 전송이 사용되기 때문에 네트워크 수명이 크게 늘어난다. 성능 평가 결과에 의하면, 제안한 DAMC 프로토콜은 기존의 통상적인 클러스터링 프로토콜보다 네트워크 수명을 대폭 연장시켜 준다는 것을 보여준다.

Ⅰ. INTRODUCTION

Wireless sensor networks (WSNs) are widely used for various applications such as environment monitoring, logistics, target tracking, military fields, home networks, and industrial diagnosis [1-5]. A WSN consists of many battery-powered sensor nodes that sense their surroundings and send the sensed data to a sink node or base station. In many WSNs, the batteries are difficult to replace and, even if replaceable, the replacement cost is very high [6]. Thus, reducing energy consumption in sensor nodes is very important for prolonging network lifetime.

In WSNs, routing is the process of forwarding data gathered by sensor nodes to the sink or base station. A WSN consists of a lot of sensor nodes, and it is inefficient for all the sensor nodes to send their sensed data to the single sink node or base station directly. Instead, the sensor nodes are grouped as clusters, and every sensor

node sends its sensed data to its cluster head (CH). Then, the CHs send the aggregated data to the sink. Such a hierarchical routing is energy-efficient compared to the flat routing that each sensor delivers data sensed by itself to the sink directly.

The typical hierarchical routing or clustering protocols are low energy adaptive clustering hierarchy (LEACH) [7], low-energy adaptive cluster hierarchy centralized (LEACH-C) [8], hybrid, energy-efficient distributed (HEED) [9], base station controlled dynamic clustering protocol (BCDCP) [10], threshold sensitive energy-efficient sensor network protocol (TEEN) [11], hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks (APTEEN) [12], proxy-enable adaptive clustering (PEACH) [13], cluster-chain based protocol (ECCP) [14], tree-based clustering (TBC) [15], and balanced clustering algorithm (BCA) [16]. The well known LEACH is the pioneer clustering protocol in WSNs, and

TBC is the most advanced clustering scheme for uniformly deployed WSNs. The recently developed BCA is a single-hop clustering scheme targeted for irregularly deployed WSNs. The existing clustering algorithms will be reviewed in more detail in Chapter II.

In many applications such as environment monitoring, sensor nodes can be irregularly deployed due to some limited condition. For example, when the sensors nodes are deployed over a mountain area by a helicopter, there is the possibility that they may be irregularly deployed. Such an irregularly deployed WSN, the sensing area or coverage area of each cluster varies region by region, i.e., there are many small-area clusters in dense regions and a few large-area clusters in sparse regions. In BCA [16], equal-size clustering is achieved even in irregularly deployed WSNs and the excessively redundant nodes are turned into sleep mode to save energy and to prolong network lifetime. In BCA, however, the single-hop transmission from sensor nodes to their CH needs more energy consumption compared to multihop transmission in a cluster because transmission power is exponentially increased with distance. On the other hand, TBC [15] implements a multi-level tree within a cluster enabling multihop transmission, but it does not take the irregular deployment into consideration resulting in severely conflicted transmissions and unnecessary energy consumption in dense regions.

In this thesis, a density-aware multihop clustering (DAMC) protocol is proposed for irregularly deployed sensor networks to reduce energy consumption and prolong network lifetime. The node density in this thesis is defined as the number of nodes within the node's sensing range divided by the node's sensing area. During the initial network configuration, every node calculates the node density and determines the probability that it becomes a CH based on the node density so that CHs are distributed evenly over the network area and every cluster has almost the same coverage area. Excessively redundant nodes are turned into sleep mode to save energy. Then, a multi-level tree in each cluster is constructed for low-energy multihop transmissions. In the proposed DAMC, the network lifetime can be significantly prolonged because the unnecessary redundant sensing and transmissions are reduced remarkably and the multihop transmissions are used rather than single-hop transmissions in clusters.

According to the simulation results, the proposed DAMC outperforms the conventional clustering protocols by up to 85 percent in terms of network lifetime in the given simulation setting. The network lifetime in our performance study is defined as the time duration until half of the sensor nodes die due to the energy depletion of battery.

The rest of this thesis is organized as follows: In the following chapter, the existing clustering protocols are reviewed in detail. In Chapter III, the operating principles and characteristics of the proposed DAMC protocol are discussed step by step. In Chapter IV, the performance of DAMC is evaluated via extensive computer simulation and compared to the conventional schemes. Finally, the thesis is concluded in Chapter V.

Ⅱ. RELATED WORKS

For more than a decade, many clustering algorithms based on randomness have been studied. Since the pioneer clustering protocol LEACH was introduced [7], more advanced clustering algorithms have been proposed so far [8]-[16]. In this Chapter, they are reviewed with respect to major characteristics and improvements.

A. LEACH

In the LEACH protocol [7], each round consists of set-up phase and steady-state phase. Clusters are formed during the set-up phase, and the sensed data are periodically delivered to the sink through CHs during the steady-state phase.

In LEACH, CHs are elected probabilistically every round. Every sensor node generates a random number between zero and one and, then, it becomes a CH if the generated number is less than the calculated threshold value. For a node n, the threshold value $T(n)$ at the r-th round is calculated by

$$T(n)=\begin{cases}\dfrac{p}{1-p(r \bmod \frac{1}{p})}, & \text{if } n\in G\\ 0, & \text{otherwise}\end{cases} \tag{1}$$

where the given parameter p is the probability that a sensor node becomes a CH and G is the set of sensor nodes that have not been chosen as a CH for $1/p$ rounds. If a node n has not been chosen as a CH for the last $1/p$ rounds, $T(n)$ is calculated by (1) and, if the generated random number is less than $T(n)$, the node becomes a CH at the current round; otherwise, $T(n)$ is zero and the node n is not elected as a CH at the current round.

Once CHs are chosen according to the above procedure, every CH broadcasts that it has becomes a CH. Then, sensor nodes send a join message to the nearest CH based on the received signal strength of the broadcast messages.

In the steady-state phase after cluster formation, sensor nodes send the sensed data to their CHs periodically in accordance with the TDMA (Time Division Multiple Access) schedule assigned by their CHs. CHs aggregate the received data and send the aggregated data to the sink node.

Such a series of procedural steps are repeated every round. That is, the CHs are rotated per round because they consume more energy than normal sensor nodes. This makes all the nodes consume energy as evenly as possible, resulting in increased network lifetime. However, when sensor nodes are irregularly deployed over the network area, the balanced energy consumption is not possible due to unbalanced clustering.

B. TBC

TBC protocol is an advanced form of TREEPSI [17] which all nodes constitute trees, it forms a cluster that root nodes perform as a cluster head and constitute multi-level trees in cluster. The CH is elected in the same manner as in the LEACH protocol. The broadcast and join messages are also similar to those in LEACH, which are sent by CHs and normal sensor nodes, respectively. Unlike LEACH, however, the location information of the sensor node is included in the join message.

By receiving the join messages from sensor nodes, the CH finds the farthest sensor node, and the distance between the CH and the farthest sensor node is denoted as d_{max}. The maximum distance d_{max} is divided by the tree depth a, where a is also called tree height or the maximum level of the tree. Therefore, the average transmission distance d_{avg} between the node and its parent node in the tree can be represented by

$$d_{avg} = \frac{d_{\max}}{\alpha}.$$

(2)

The CH is at level 0 in the tree and member nodes are at the specific level according to the distance from the CH. Figure 1 shows an example of constructing a tree in TBC when *a* is 3. Once the cluster is divided into *a* concentric circles as shown in Figure 1, each sensor node selects an upper-level node with the minimum distance from the node itself as its parent node. Finally, a single tree is generated.

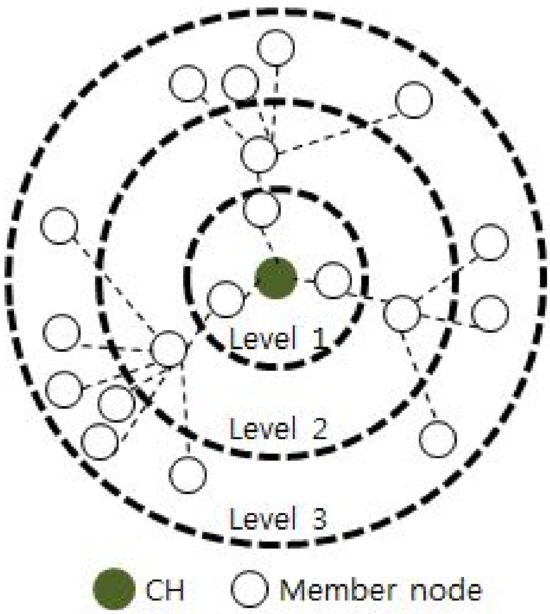


Figure 1. An example tree in TBC when α=3

C. BCA

In the BCA protocol [16], every cluster area is almost the same even when sensor nodes are deployed irregularly over the network area. The balanced clustering is achieved by electing the CH on the basis of relative node density. For a node *n*, the relative node density *D(n)* is given by dividing node density by network density, where the node density is the ratio of the number of nodes within the node's sensing range over the node's sensing area and the network density is the ratio of the total number of nodes in the network over the network area. Therefore, *D(n)* can be represented by

$$D(n) = \frac{F/(\pi R^2)}{N/A} = \frac{F/N}{\pi R^2/A}, \tag{3}$$

where *F* is the number of nodes within the node's sensing range, *N* is the total number of nodes in the network, *R* is the sensing range, and *A* is the network area.

The CH is selected according to a new threshold taking the *D(n)* into consideration. That is, for a node *n*, the new threshold value $\widetilde{T}(n)$ at the r-th round is calculated by

$$\widetilde{T}(n) = T(n) + \frac{mT(n)}{N}\left(\frac{1}{D(n)} - 1\right), \tag{4}$$

where *T(n)* is the same threshold value calculated in (1), *N* is the total number of nodes in the network, and m is the number of living nodes in the network.

In the region where the node density is high, $\widetilde{T}(n)$ is decreased compared to *T(n)* and, thus, a less number of CHs are selected every round. This results in balanced clustering even when sensor nodes are irregularly deployed. After cluster formation, if the number of nodes in a cluster exceeds the average number of nodes per cluster in the network, the randomly chosen excessive nodes in the cluster are remained sleep every round. That is, the nodes not included in clusters in dense regions are remained sleep every round. However, when sensor nodes are regularly deployed in the network area, BCA incurs extra overhead for calculating the node density unnecessarily.

D. Other Clustering Protocols

LEACH-C [8] is a centralized version of LEACH. That is, the base station elects cluster heads and forms clusters. All nodes in the network send a message including position and residual energy information to the base station. Based on the information, the base station selects cluster heads and divides all nodes to the clusters. Then, the base station broadcasts the information of clusters to all the nodes which are deployed in the network area.

HEED [9] uses some values which take into account the nodes residual energy for cluster formation. A node with more residual energy can be elected as a cluster head for prolonging network lifetime. If candidates for the cluster head have the same residual energy, then their transmission costs are compared.

In BCDCP [10], the complex calculations are assigned to the base station as in LEACHC. In cluster formation, base station elects a candidate set of cluster heads to determine cluster heads. In this scheme, cluster heads send aggregated messages to the base station on a multi-hop basis without direct transmission.

In TEEN [11], sensor nodes manage the threshold data reactively. The process which excludes the threshold value is equal to LEACH. The cluster formation process in TEEN is the same as that in LEACH. After cluster formation, cluster heads transmit the parameters of the data, the hard threshold (HT) value, and the soft threshold (ST) value to their member nodes. All nodes collect and transmit data when the value exceeds the HT value first. After exceeding HT, nodes collect and transmit data only when the measured data exceeds ST.

APTEEN [12] combines the advantages of LEACH and TEEN. As a hybrid protocol, APTEEN unites the data transmission according to the threshold value of TEEN and the periodic data transmission of LEACH. After cluster formation, the cluster heads transmit the threshold value and parameters that include the TDMA schedule time to the member nodes.

PEACH [13] is a clustering technique that considers remaining energy of nodes. It selects a cluster head and proxy node when the round begins. if the remaining energy of the cluster head is lower than threshold value, it delegates cluster head's job to proxy nodes, which can solve the problem found in LEACH that dosen't consider remaining energy.

ECCP [14] is a chain-based protocol which elects cluster head with weight value by using distance of neighboring nodes and residual energy of nodes. Then, it not only constitutes a chain within a cluster, but also connects all cluster heads with a chain and transmits data.

More recently, some works on clustering have been reported in the literature [18-20] even though they do not achieve a major quantum jump. They mainly focus on the improvement of energy efficiency because the energy efficiency is one of the most important design criteria for prolonging network lifetime in battery-operated wireless sensor networks. In addition, they do not take the irregular deployment of sensor nodes into consideration yet.

Ⅲ. DENSITY-AWARE MULTIHOP CLUSTERING

In this Chapter, the operating principles and characteristics of the proposed DAMC protocol are discussed in detail. CH selection, sleep node selection, tree construction, and sensing and data transmission are presented step by step. As in TBC [15], it is assumed that each node has the location information of itself and it can adjust its transmission power depending on the distance to its receiver.

A. Cluster Head Selection

For density-aware clustering in an irregularly deployed WSN, DAMC considers the node density for cluster formation as in BCA [16]. As mentioned in Chapter I, the node density in this thesis is defined as the number of nodes within the node's sensing range divided by the node's sensing area. During the initial network configuration just after network deployment, every sensor node calculates the node density and determines the probability that it becomes a CH based on the node density. As a result, CHs are distributed evenly over the network area. This means that every cluster has almost the same coverage area.

The number of CHs is decided in accordance with the probability that a sensor node becomes a CH. Usually, the probability is initially set up when sensor nodes are deployed. Just after CHs are probabilistically chosen, every CH broadcasts that it has become a CH. Each sensor node can receive multiple broadcast messages from multiple CHs and calculate their received signal strength. Then, each sensor node sends a join message to the nearest CH based on the received signal strength of the broadcast messages. By doing so, cluster membership is determined and every sensor node belongs to a cluster. However, the number of nodes in a cluster varies cluster by cluster because the node density differs region by region in the irregularly deployed WSN.

B. Sleep Node Selection

Immediately after CHs are selected, some nodes in densely populated clusters should be turned into sleep mode to reduce unnecessary energy consumption and severely conflicted transmissions in densely deployed regions. That is, if the number of nodes in a cluster exceeds the average number of nodes per cluster in the network, the randomly chosen excessive nodes in the cluster remain in sleep mode. The sleep nodes are randomly chosen every round.

As a matter of fact, the number of sleep nodes in a cluster is recalculated depending on the number of living nodes as the number of dead nodes is increased over time. That is, the number of sleep node in a cluster, $\widetilde{S}(u,m)$, is calculated by

$$S(u,m) = u - \frac{m}{c} \tag{5}$$

and

$$\widetilde{S}(u,m) = \begin{cases} \left\lceil \dfrac{S(u,m) \times m}{N} \right\rceil, & \text{if } S(u,m) > L \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where u is the number of nodes in a cluster, m is the number of living nodes in the network, c is the expected number of clusters, N is the total number of nodes in the network, and L is the minimum number of living nodes in a cluster for network operation.

After the CH selects the sleep nodes randomly, it broadcasts the identifiers of sleep nodes to all member nodes. Then, the sleep nodes go into sleep mode during the round.

C. Tree Construction

For multihop clustering of the selected member nodes without sleep nodes in a cluster, a multi-level tree is constructed in a cluster as in [15], in which the CH is the root node. When each sensor node sends a join message to the nearest CH during CH selection, the location information of the sensor node is also included in the join message. Once the cluster is divided into *a* concentric circles by the CH, where *a* is tree height, the CH informs its active members of the necessary information for parent node selection. Then, each sensor node selects an upper-level node with the minimum distance from the node itself as its parent node. After tree construction, the CH broadcasts the TDMA schedule to all the active member nodes. Figure 2 shows an example tree composed of 16 active nodes in a 20-node cluster when tree height (*a*) is set to 3.

The multi-level tree can reduce energy consumption significantly because a series of multihop short-distance transmissions consume much less energy than a single-hop long-distance transmission. Note here that the transmitted signal is usually attenuated in inversely proportional to the fourth power of the distance. Figure 3 shows examples of cluster formation in an irregularly deployed WSN, in which four clustering schemes of LEACH, TBC, BCA and the proposed DAMC are compared schematically. In the figure, the nodes labeled S are sleep nodes in the densely populated clusters. The sleep nodes are randomly chosen every round.

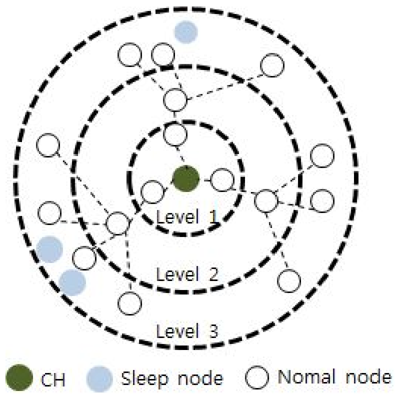


Figure 2. An example tree of 16 active nodes (α=3)

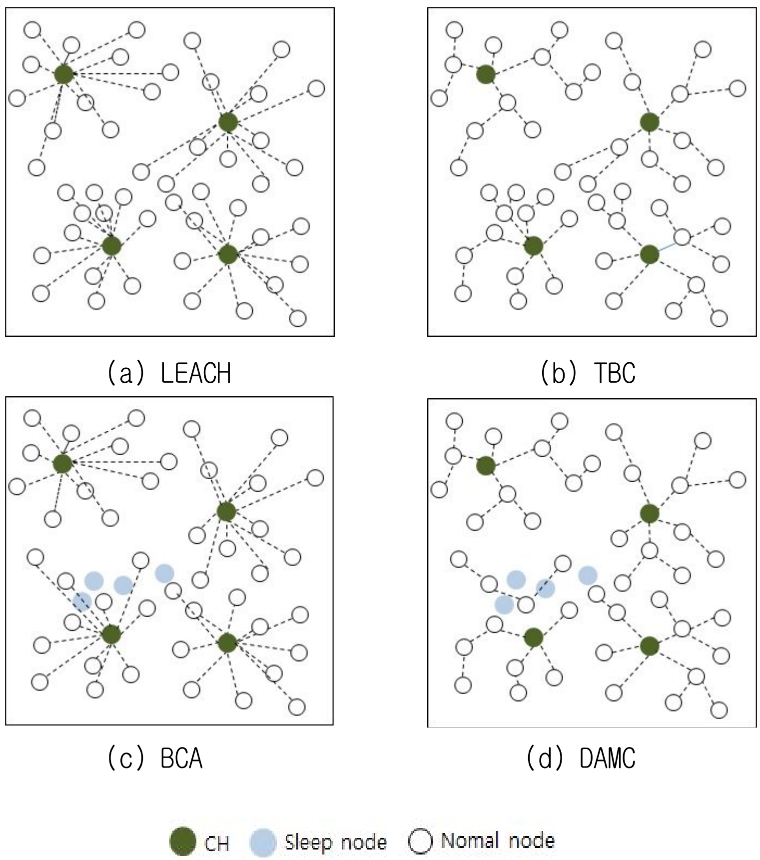


Figure 3. Examples of cluster formation in an irregularly deployed WSN

D. Data Gathering and Transmission

After the cluster formation including tree construction, sensor nodes send the sensed data to their CHs periodically in accordance with the TDMA schedule. Each CH aggregates the received data and sends the aggregated data to the sink node by using the CSMA (Carrier Sense Multiple Access) protocol. Once a multihop cluster is formed, the data gathering and transmission are repeated in rounds as shown in Figure 4. In the figure, the back-slashed boxes and the subsequent gray boxes indicate the communications from cluster members to their CHs and the communications from CHs to the sink node, respectively. It should be also noted that the node density detection is carried out only once at the beginning, but the cluster formation is done in every round.

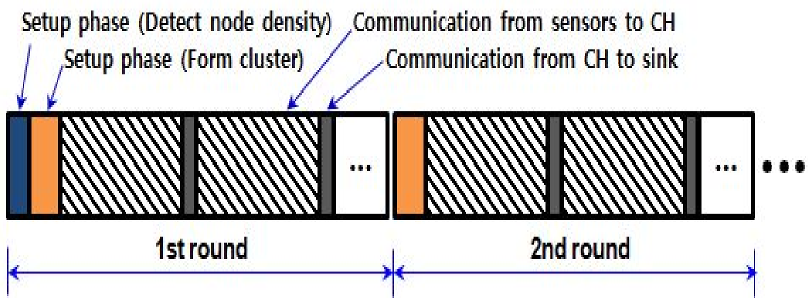


Figure 4. Rounds of the proposed DAMC

In summary, the energy consumption in DAMC can be significantly reduced, resulting in prolonged network lifetime, because the unnecessary redundant sensing and transmissions are reduced remarkably and the low-energy multihop transmissions are used instead of single-hop transmissions from sensor nodes to CH in a cluster.

E. Comparison of Clustering Protocols

In this sation, the four clustering protocols of LEACH, TBC, BCA and the proposed DAMC are qualitatively compared in terms of various technical aspects. Table 1. comparatively summarizes the major features and characteristics of the four protocols.

Table 1. COMPARISION OF CLUSTERING PROTOCOLS.

Protocol	LEACH	TBC	BCA	DAMC
CH selection criteria	Probability	Probability	Node density & probability	Node density & probability
Performance in irregular deployment	Low	Low	Middle	High
Data delivery latency	Short	Middle	Short	Middle
Topology within a cluster	Star	Tree	Star	Tree
Impact of node failure	Low	Middle	Low	Middle
Energy consumption at Chs	High	Middle	Middle	Low

For irregularly deployed WSNs, BCA and DAMC are better than LEACH and TBC because the node density is additionally considered in selecting CHs. On the other hand, the multi-level tree structure in TBC and DAMC results in not only the increased end-to-end latency of data delivery but also more loss of data when an upper-level node is failed. Even so, DAMC achieves higher performance and lower energy consumption than the other three protocols. This will be clearly shown in the next chapter according to the comparative simulation.

Ⅳ. PERFORMANCE EVALUATION

In this chapter, the performance of DAMC is evaluated via computer simulation using Matlab and compared to the conventional clustering schemes of LEACH [7], TBC [15] and BCA [16]. As described earlier, the popular LEACH is a pioneer protocol in clustering for WSNs, TBC is the most advanced clustering scheme for uniformly deployed WSNs, and the recently developed BCA is a single-hop clustering scheme targeted for irregularly deployed WSNs.

A. Simulation Environment

In our simulation, 200 sensor nodes are deployed over the network area of 100 × 100 ㎡. The sink node (or base station) is fixed at the location (125, 75), and the initial energy of each senor node is set to 2 J. In our simulation, six irregular deployments are experimented as shown in Figure 5: (1) 100 nodes are deployed in the region of 50 × 50 ㎡ and the other 100 nodes are deployed in the other regions, (2) 100 nodes are deployed in the region of 25 × 25 ㎡ and the other 100 nodes are deployed in the other regions, (3) 200 nodes are deployed according to the normal distribution with mean of (50, 50) and variance of (±10, ±10), (4) 200 nodes are deployed according to the normal distribution with mean of (50, 50) and variance of (±20, ±20), (5) 200 nodes are deployed according to the exponential distribution with mean of (50 ± 10, 50 ± 10), and (6) 200 nodes are deployed according to the exponential distribution with mean of (50 ± 20, 50 ± 20).

In our experiment, the energy consumption model [21] is as follows: The free space (*fs*) model is used if the distance is less than a threshold d_0; otherwise, the multipath (*mp*) model is used. Hence, when transmitting *k* bits of a message along with distance d, the energy consumption can be calculated by

$$E_{Tx}(k,d)=E_{Tx-elec}(k)+E_{Tx-amp}(k,d) \\ =\begin{cases} kE_{elec}+k\varepsilon_{fs}d^2, & \text{if } d<d_0 \\ kE_{elec}+k\varepsilon_{mp}d^4, & \text{otherwise} \end{cases} \tag{7}$$

where d_0 is set to 87 m as in [15]. The energy consumption for receiving k bits of data is calculated by

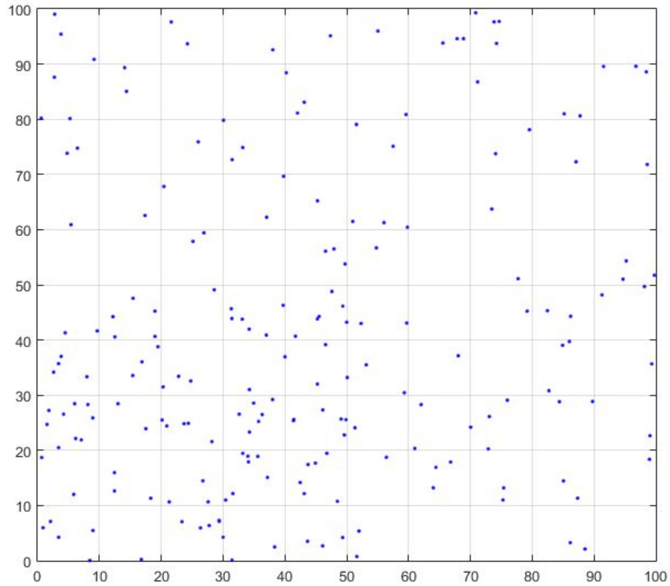
$$E_{Rx}(k,d)=E_{Rx-elec}(k)=kE_{elec} \tag{8}$$

In (7) and (8), E_{elec} is the radio electronics energy depending on digital coding, modulation, filtering and spreading of the signal. ε_{fs} and $\varepsilon_{mp}$are constant values for the amplifier energy depending on the distance to the receiver and acceptable bit-error rate.

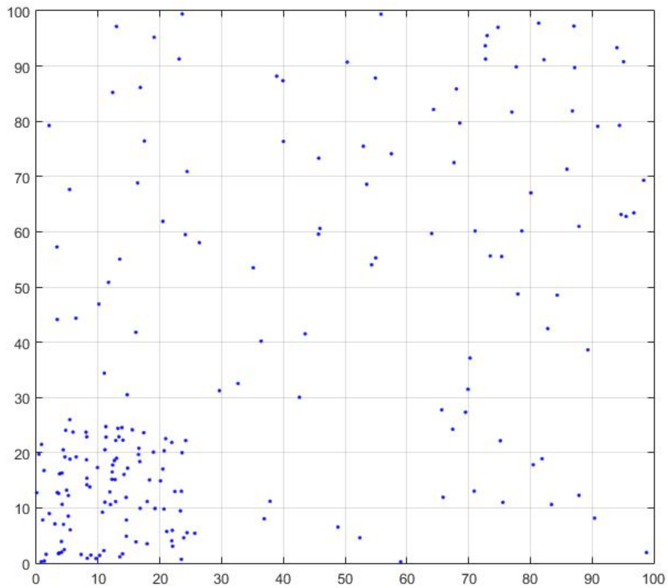
The parameters used in our simulation are summarized in Table II. In the table, E_{sense} is the energy consumption required for sensing and E_{da} is the energy consumption for data aggregation. The simulations were performed 100 times for each experiment and the mean value of results was used as the simulation results.

Table 2. SIMULATION PARAMETER

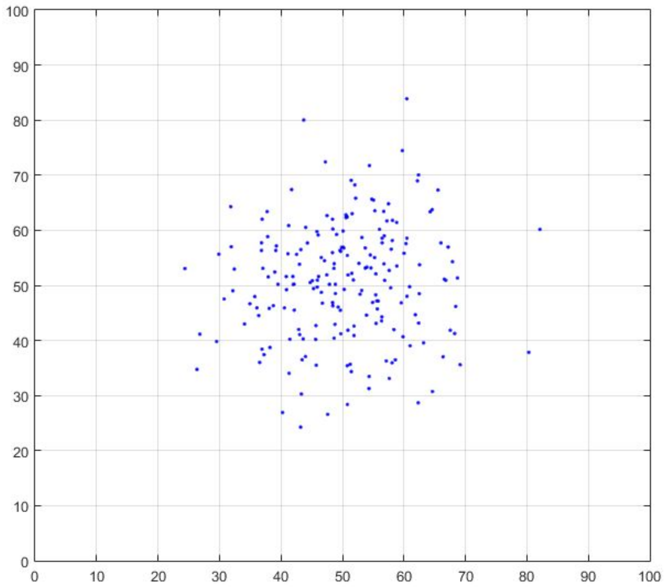
Parameter	Value
Network area	100 × 100 m^2
Location of sink	(125, 75)
Number of nodes	200
Number of clusters	10
Initial energy	2 J
Esense	5 nJ/bit
Eda	5 nJ/bit
Eelec	50 nJ/bit
Efs	10 pJ/bit/m^2
Emp	0.00013 pJ/bit/m^4
Sensing range	10 m
Maximum transmission range	136 m



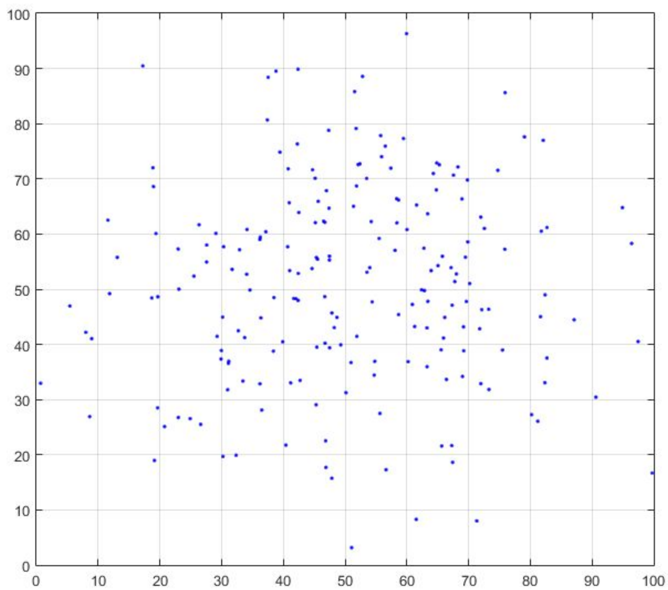
(a) 100 nodes are deployed in the region of 50 × 50㎡.



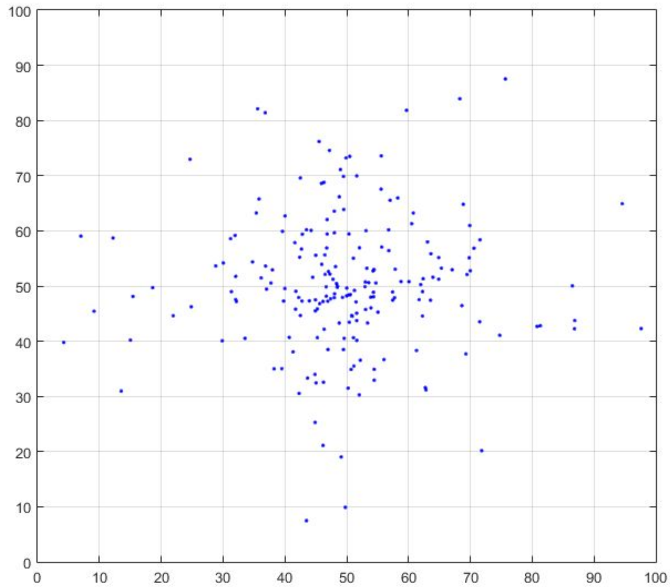
(b) 100 nodes are deployed in the region 25 × 25㎡.



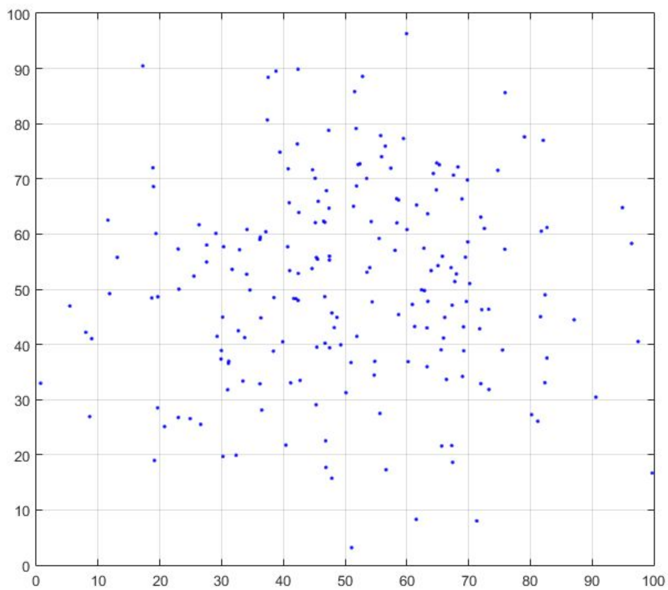
(c) normal distribution with mean (50, 50) and variance (±10, ±10).



(d) normal distribution with mean (50, 50) and variance (±20, ±20).



(e) exponential distribution with mean (50±10, 50±10).



(f) exponential distribution with mean (50±20, 50±20).

Figure 5. Six irregular deployments of 200 nodes for simulation.

B. Simulation Results and Discussion

In our performance study, the network lifetime is extensively evaluated because it is the most important metric in WSNs. The network lifetime in our performance study is defined as the time duration until half of the sensor nodes die due to the energy depletion of battery. So, the number of living nodes is observed with respect to round progress.

Figures 6 to 11 show the number of living nodes along with round for the six scenarios of irregular deployment described in Chapter IV-A. From the six figures, it is clearly shown that the proposed DAMC outperforms the three conventional schemes of LEACH, TBC and BCA.

Figures 6 and 7 show the number of living nodes along with round for the two exceptional scenarios of irregular deployment. In the first deployment that 100 nodes are deployed in the region of 50 × 50 m^2 and the other 100 nodes are deployed in the other regions, the network lifetime is 16 to 32 percent longer than the others. In the second deployment that 100 nodes are deployed in the region of 25 × 25 m^2 and the other 100 nodes are deployed in the other regions, the network lifetime is 26 to 57 percent longer than the others. That is, it can be easily inferred that the improvement is better and better as the irregularity increases.

Figures 8 and 9 show the number of living nodes along with round for the two normal distribution scenarios of non-uniform deployment. In the third deployment that 200 nodes are deployed according to the normal distribution with mean of (50, 50) and variance of (±10, ±10), the network lifetime is 6 to 85 percent longer than the others. In the fourth deployment that 200 nodes are deployed according to the normal distribution with mean of (50, 50) and variance of (±20, ±20), the network lifetime is 3 to 31 percent longer than the others. That is, it can be easily inferred that the improvement is better and better as the variance decreases.

Figures 10 and 11 show the number of living nodes along with round for the two exponential distribution scenarios of non-uniform deployment. In the fifth deployment that 200 nodes are deployed according to the exponential distribution with mean of (50 ± 10, 50 ± 10), the network lifetime is 10 to 76 percent longer than the others. In the sixth deployment that 200 nodes are deployed according to the exponential distribution with mean of (50 ± 20, 50 ± 20), the network lifetime is 6 to 43 percent longer than the others. That is, it can be easily inferred that the improvement is better and better as the mean decreases.

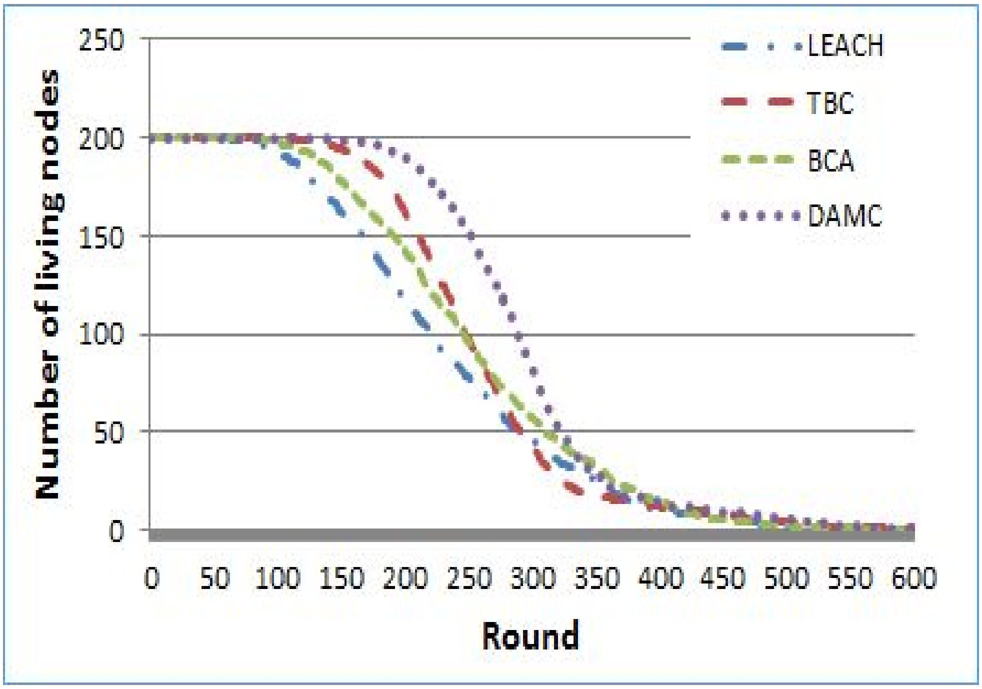


Figure 6. Network lifetime when 100 nodes are deployed in the region of 50 × 50 ㎡ and the other 100 nodes are deployed in the other regions.

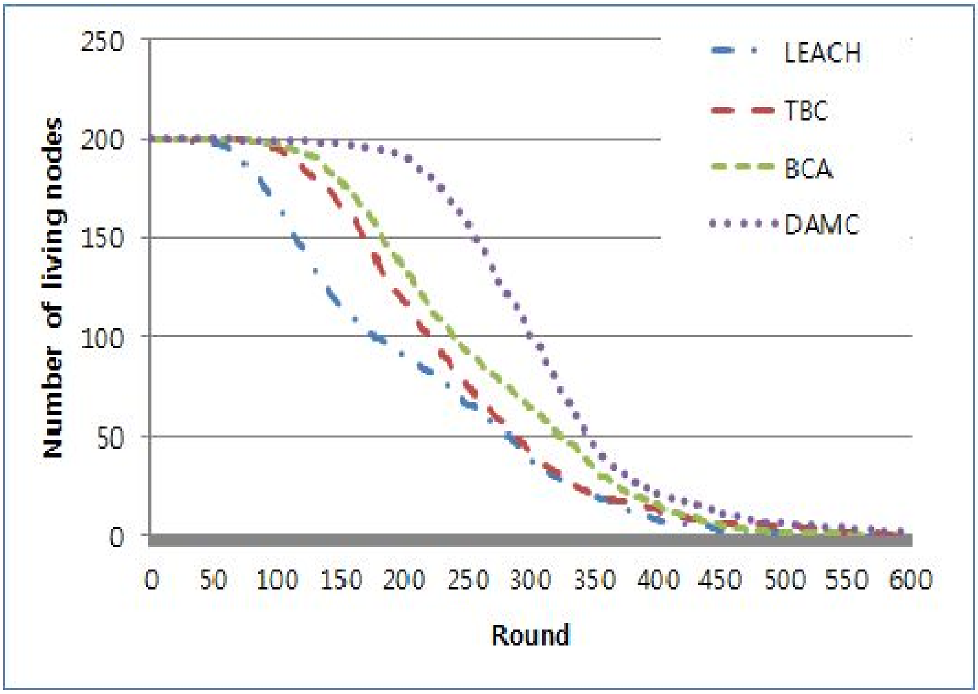


Figure 7. Network lifetime when 100 nodes are deployed in the region of 25 × 25 ㎡ and the other 100 nodes are deployed in the other regions.

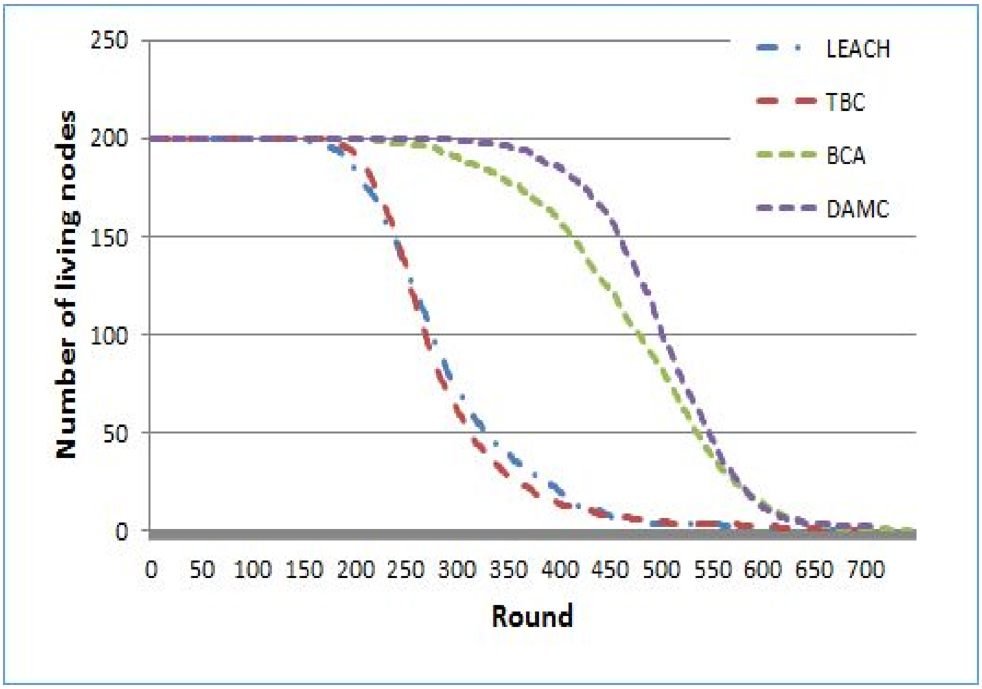


Figure 8. Network lifetime when 200 nodes are deployed according to the normal distribution with mean of (50, 50) and variance of (±10, ±10).

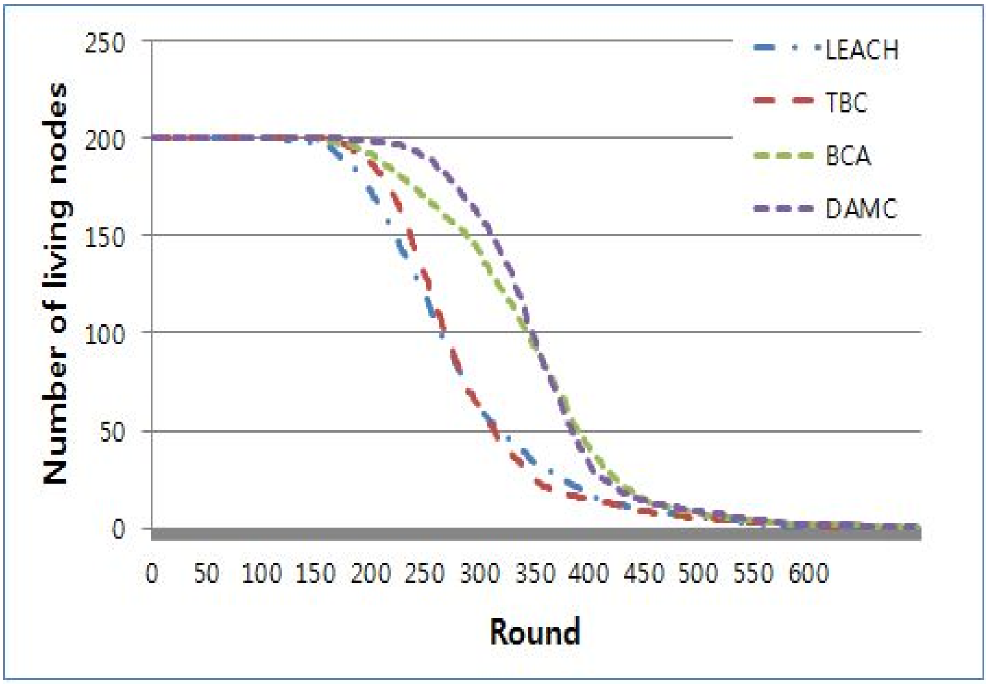


Figure 9. Network lifetime when 200 nodes are deployed according to the normal distribution with mean of (50, 50) and variance of (±20, ±20).

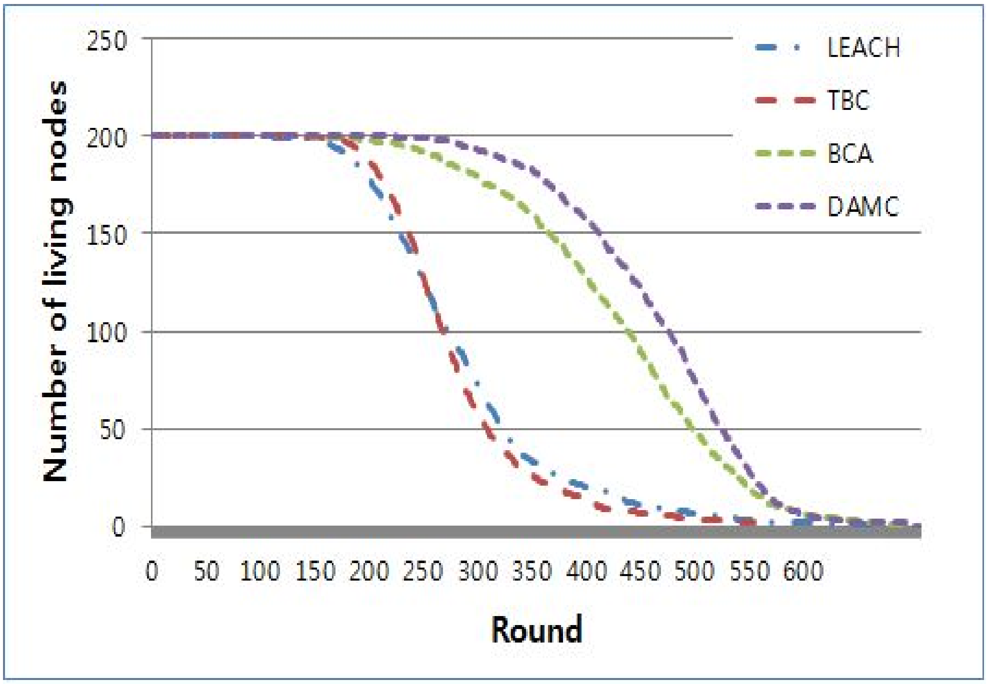


Figure 10. Network lifetime when 200 nodes are deployed according to the exponential distribution with mean of (50 ± 10, 50 ± 10).

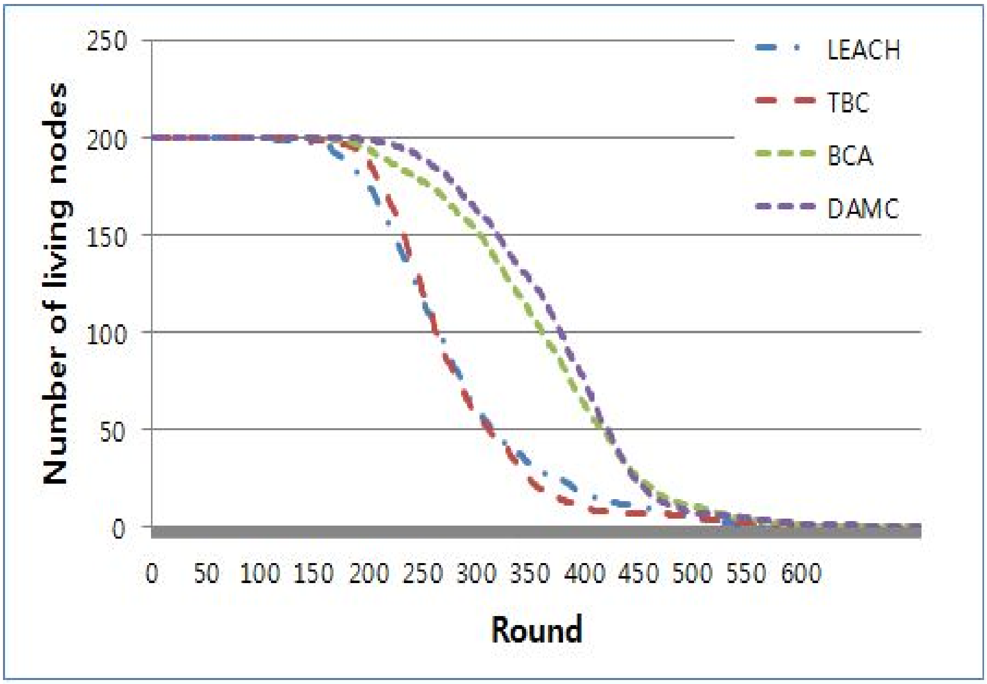


Figure 11. Network lifetime when 200 nodes are deployed according to the exponential distribution with mean of (50 ± 20, 50 ± 20).

Among the four clustering schemes, LEACH shows the worst performance in our simulation. The comparative performance of TBC and BCA depends on the irregularity. When the irregularity is relatively low, the performance difference of them is not significant. With high irregularity, however, BCA obviously outperforms TBC as shown in the two graphs. The proposed DAMC always outperforms the other three protocols.

In the proposed DAMC, the network lifetime is remarkably prolonged. CHs are distributed evenly over the network area and every cluster has almost the same coverage area. Excessively redundant nodes are turned into sleep mode to save energy. That is, the unnecessary redundant sensing and transmissions are significantly reduced. In addition, a multi-level tree in each cluster reduces energy further thanks to low-energy multihop transmissions.

Ⅴ. CONCLUSIONS

In this thesis, an energy-efficient clustering protocol called DAMC for irregularly deployed WSNs has been proposed, in which the local node density and the multi-level tree structure are exploited in every cluster. During cluster formation, excessively redundant nodes are turned into sleep mode to avoid unnecessary redundant sensing and transmissions. And the multi-level tree in each cluster enables low-energy multihop transmissions rather than long single-hop transmissions. Such effects result in significantly low energy consumption and prolonged network lifetime in DAMC. The performance study has shown that the proposed DAMC outperforms the clustering protocols such as LEACH, TBC and BCA in terms of network lifetime.

As a possible future work, we are going to investigate a more efficient tree structure in a cluster by taking residual node energy into account in addition to the node density in irregularly deployed WSNs. However, in this proposed DAMC, time delay can be occurred during the process of transmitting data from child nodes to parent nodes. In this consideration of possible problems, a study for minimizing the time delay should be conducted as well as searching methods of collecting data more efficiently.

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